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14. ABSTRACT
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15. SUBJECT TERMS
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Multipli-entangled photons from a spontaneous parametric down-conversion source

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1. ABSTRACT

In this work, we discuss a novel compact source that generates six pairs of entangled photons via spontaneous parametric down-conversion from a single pass of a pump beam through a crystal assembly. The experimental demonstrations reported are at 810 nm so as to utilize high quantum efficiency Si-APD detectors, but the design can be readily implemented in other wavelength regimes including the telecom bands near 1550 nm. An immediate application of this source enables particular multi-qubit cluster states to be generated in a highly compact unidirectional configuration. This can significantly simplify the interferometric stability, as well as feed-forward methods required in photon-based quantum logic circuitry.

Key Words: quantum, entangled photons, spontaneous parametric down-conversion

2. INTRODUCTION

Spontaneous parametric down-conversion (SPDC) in nonlinear crystals has provided the groundbreaking foundational basis for work in quantum optics (QO) over the last two decades. Experimental demonstrations of entanglement in photon pairs has more recently become of interest in quantum computational architectures that operate by principles entirely distinct from any based on classical physics. Standard type I and type II SPDC crystals are still the leading technology for the production of high mode quality photons for use in quantum optics experiments. In these sources entangled photon pairs are emitted as high energy pump photons pass through a nonlinear crystal. Multi-partite states of four or more entangled photons are generated by employing several crystals, or multiple passes through a single crystal.

In this paper we describe the novel, compact multipli-entangled photon source (designated "Schioedtei") crystal for type II SPDC which produces six pairs of photons, surpassing the typical generation of a single pair of entangled photons per pass in conventional SPDC-based sources. We first describe the experimental testbed used for evaluation and generation of entangled photons via the Schioedtei source. Next, we describe the results obtained for the prototype version I of this crystal assembly and initial results for version II. Lastly, we discuss the implications of our source design and directions for future improvements.

3. BACKGROUND

High intensity type II SPDC sources described by Kwiat [1] served as the first realizable source for the generation of entangled photons. The output of this source is comprised of two orthogonally-polarized entangled photons (signal & idler) produced upon excitation from a linearly-polarized pump laser beam. Due to the inherent birefringence of the crystal there is noticeable signal, idler walk off which leads to the familiar double ring pattern as illustrated in Figure 1. The intersections of the two orthogonally-polarized rings are regions of photon indistinguishability where entanglement

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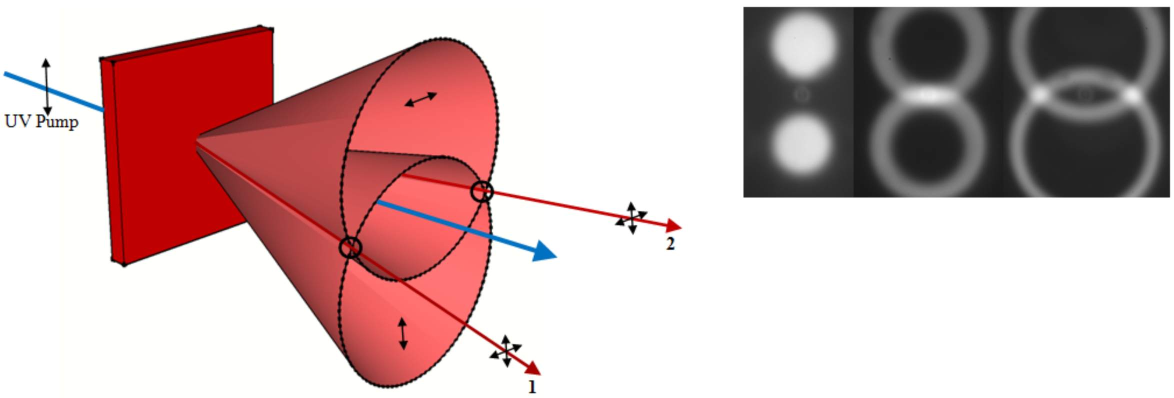
occurs. Variation of the crystal orientation changes the size and therefore the intersection points of the rings as shown in Figure 1. The typical operational configuration is collinear or tangential, where the two rings intersect at nearly 90°. This produces a Gaussian-like beam profile which gives a high coupling efficiency into optical fiber.



$$|H\rangle_1|V\rangle_2 \pm e^{i\varphi}|V\rangle_1|H\rangle_2$$

Figure 1. (left) Type-II SPDC photon source and resulting (unnormalized) entangled photon polarization state. (right) In-house laboratory images showing SPDC ring evolution with the variation of the crystal orientation.

Type I crystals have been used for many years as frequency converters for second harmonic generation (SHG). The signal and idler photons produced from type I down-conversion are both orthogonal with respect to the linear pump beam. The fact that the signal and idler photons both have the same polarization mitigates the walk-off problem due to the birefringence of the crystal. Varying the crystal orientation produces either a single output cone or single beam with respect to the linear pump beam. Kwiat first described the use of type I crystals as a feasible source for SPDC-generated entangled photons with the development of the type I pair design [2]. This consisted of a pair of type I crystals rotated with their optic axes orthogonal to each other. This allows for the production of two orthogonally-polarized cones of photons (see Figure 2) which overlap upon correct rotation of the crystal. The pump must also be changed from purely horizontal or vertical polarization as for a single type I crystal, to 45° to excite both crystals. Since signal, idler walk-off due to birefringence is not an issue in type I crystals this source is more efficient than a type II source. This is due to the longer interaction length in which the photons remain entangled over the crystal length, thus allowing for longer crystals. Further, in a configuration in which the two rings overlap photons along the entire ring are indistinguishable allowing for any diametrically opposite pair (diametric pair) to be collected and utilized [3]. The fundamental collection limit of this source comes down to hardware, namely how many apertures can be stationed in front of the ring for collection of the diametric pairs.

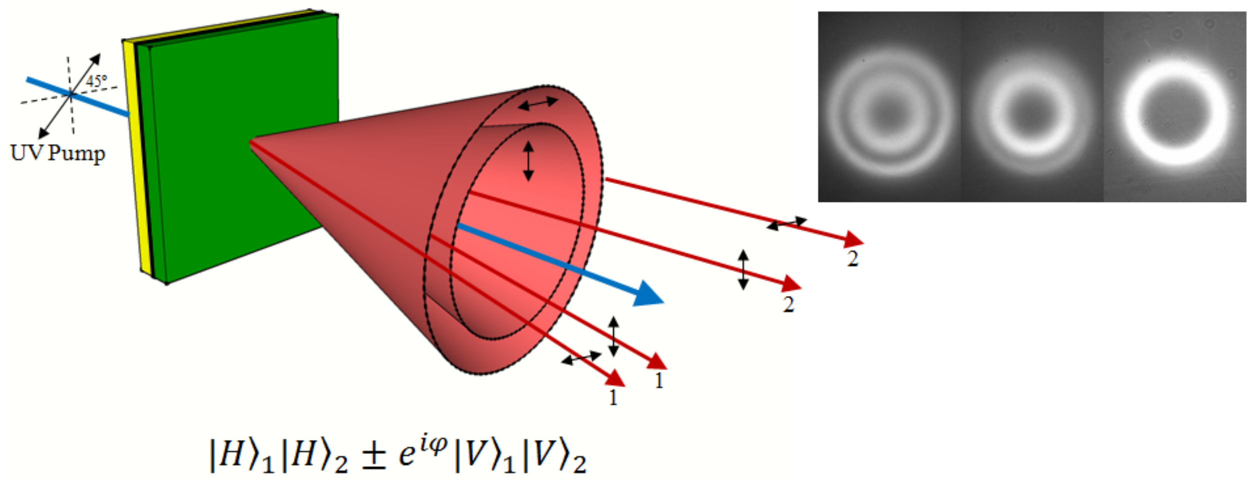


Figure 2. (left) Type-I pair SPDC photon source and resulting (unnormalized) entangled polarization state. (right) In-house laboratory images showing SPDC ring evolution with the variation of the crystal orientation.

Various other schemes have been developed for increasing the useable output of type II to limits approaching that of type I. Bitton et. al. describe a type II pair with each type II optical axis rotated 180° with respect to each other; see Figure 3 [4]. This allows the linear pumping scheme to remain unchanged while allowing both crystals to produce one set of rings each with the polarization orientation rotated 180°. In this configuration any selected diametric pair across either ring is indistinguishable and useable, and the fundamental size of the collection apertures becomes the limiting factor in the number of diametric pairs that can be collected.

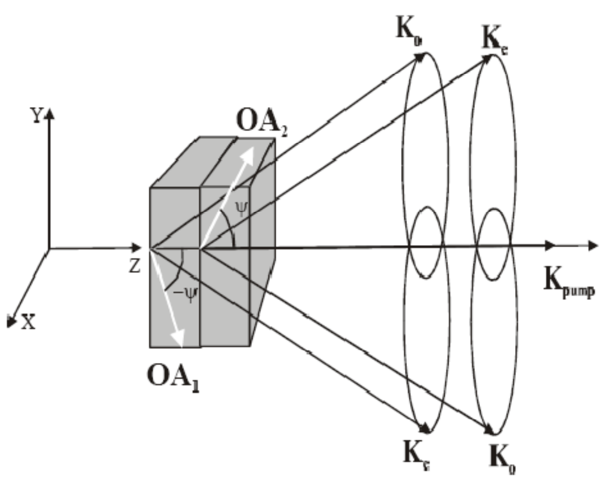


Figure 3. Type-II entangled photon pair as described by Bitton et. al. [4].

U'Ren et al. described a type II crystal assembly (see Figure 4) that is designed for group velocity matching (GVM) of the pump and signal/idler wave packets, thereby removing the spectral distinguishability of the photons [5]. The symmetric nature of the joint spectral function of the entangled photons produced from this crystal removes the need for spectral filtering of the down-converted photons inherent to all current SPDC sources. This increases the percentage of useable entangled photons produced from a type II crystal.

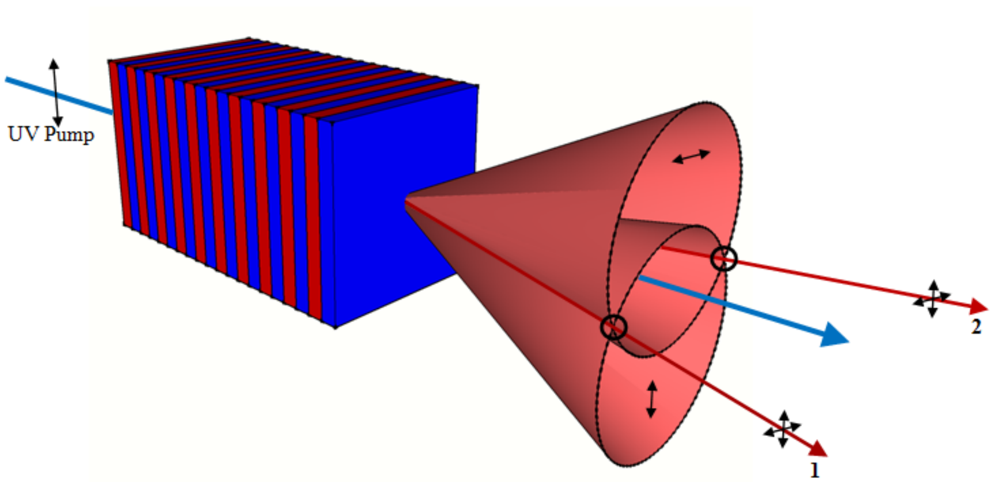


Figure 4. Type-II custom assembly showing alternating BBO (red) and calcite (blue) segments.

With an ever increasing need for larger numbers of entangled photon pairs, new sources must either produce more photons or the efficiency must be increased to compensate for the spontaneous nature of the source. A particular area of interest where larger numbers of photons are desired is photon-based cluster state quantum computing where individual pairs of photons are entangled together to form larger arrays of entangled photons. Typically, large numbers of single pairs are generated by cascading or multi-passing the excitation beam thru SPDC sources as shown in Figure 5 [6]. In a typical configuration each of these sources produces a single pair of entangled photons. Thus obtaining a larger photon number requires an increase in the overall footprint size of the experimental setup. Hyper-entanglement, entangling in more than one degree of freedom of the photon (e.g. polarization, spectral, spatial, orbital angular momentum, etc …), is another option that has been strongly considered as a means to increase quantum bit (qubit) numbers [7]. The spontaneous nature of photon generation is mitigated in this case, but at the expense of an increase in the physical hardware required to implement the hyper-entanglement.

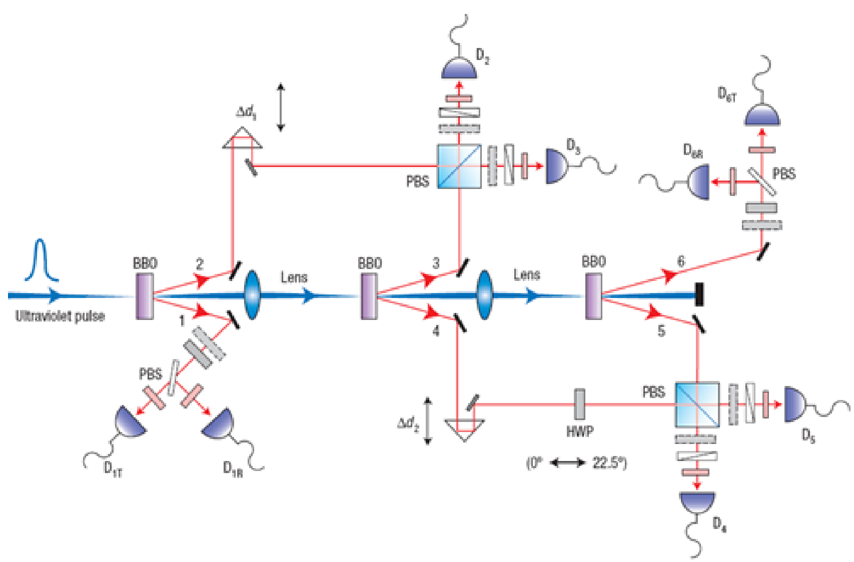


Figure 5. Experimental configuration for the generation of entangled photon cluster states [6].

4. THE SCHIOEDTEI MULTIPLI-ENTANGLED PHOTON SOURCE

4.1 SPDC Schioedtei Crystal Assembly

The Schioedtei crystal assembly design is a novel adaptation of a typical type II SPDC source. The Schioedtei source (designated simply as "Schioedtei" henceforth) consists of a pair of two type II non-collinear phase-matched SPDC crystals cut for degenerate down-conversion whose optic axes are rotated orthogonal with respect to one another as in Figure 6.

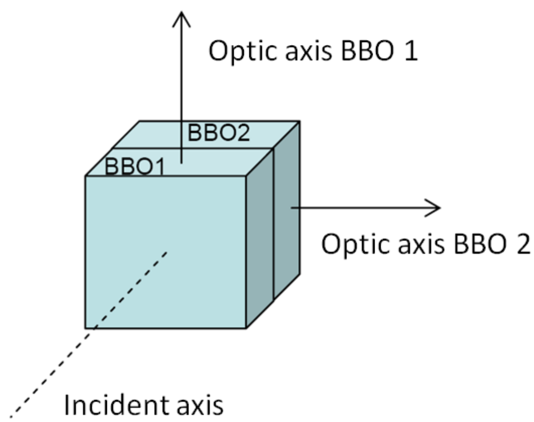


Figure 7. Type-II SPDC Schioedtei crystal assembly.

When the crystal pair is excited with an incident 45° polarized pump beam one pair of rings is produced from each of the type II crystals. Each pair of rings is orthogonal to the other resulting in 12 intersection points (or simply "points") where indistinguishable photons are produced. Referring to Figure 7, the indicated points marked 5, 6 and 7, 8 are the typical Bell states, $\left|B\right\rangle_{5,6\,(7,8)} = \frac{1}{\sqrt{2}}\left(\left|HV\right\rangle_{5,6\,(7,8)} \pm \mathrm{e}^{i\varphi}\left|VH\right\rangle_{5,6\,(7,8)}\right)$, with one pair arising from crystal 1, and the second pair produced from crystal 2. The points indicated by 1, 2, 3, 4 are the product of two bell states, $\left|\Psi\right\rangle_{1,2,3,4} = \frac{1}{2}\left(\left|HH\right\rangle_{1,2} + \mathrm{e}^{i\varphi}\left|VV\right\rangle_{1,2}\right)\left(\left|HH\right\rangle_{3,4} + \mathrm{e}^{i\varphi}\left|VV\right\rangle_{3,4}\right)$, produced from photons from both crystal 1 and 2 concurrently. Points 9, 11 and 10, 12 are $\left|\mathrm{VV}\right\rangle_{9,11}$ and $\left|\mathrm{HH}\right\rangle_{10,12}$ states produced from photons from crystal 1 and 2 concurrently.

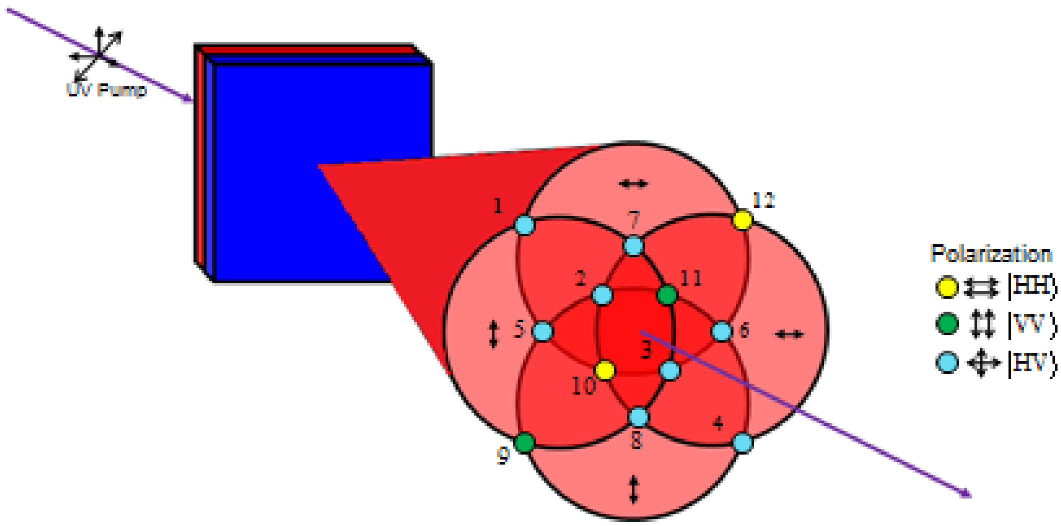


Figure 7. Type-II SPDC Schioedtei source. See text for discussion of the intersection points of the overlapping rings.

The prototype version of the Schioedtei assembly was constructed in-house from two 8x8x2 mm type II beta-Barium borate (β-BBO) crystals phase matched (at angles of theta = 41.9°, phi = 30°) for 810 nm spontaneous parametric down-conversion. Each of the crystals had a dualband AR coating for 405/810 nm on all faces and were placed in physical contact with each other in a constructed housing. A second version (version II) of the assembly was constructed by an outside vendor since optically contacting the crystals is not an in-house capability. Version II was dualband AR coated for 405/810 nm only on the exterior faces of the assembly.

The experimental setup used for testing of the Schioedtei assembly is shown in Figure 8. The experimental configuration required for testing with a pulsed pump consisted of a 15 watt continuous wave Vandate laser operating at 532 nm (Millenia PRO 15sJ) pumping a 3.5 W 100 fs Ti:Sapphire laser operating at 810 nm (Tsunami 3960-15HP), passing through an SHG unit (Inspire Blue FM), to produce ~100fs pulses at 405 nm with an average power of 1.4 W. The 405 nm pulses served as the input excitation beam for the Schioedtei assembly after first passing through a 6 mm quartz pre-compensator and a half-wave plate set to 22.5° to rotate the input linear polarization to the required 45° for equal excitation of the crystals. This configuration also allowed for continuous wave (CW) mode testing in which a 100 mW 405 nm diode laser was inserted into the setup via a flip mirror and the pre-compensator was then removed before the Schioedtei assembly. The residual pump beam was collected in a beam dump, although it could just as easily been redirected with a mirror to pump further crystal stages. The generated cones then propagated across approximately 0.5 meters of free space to obtain the useable spatial separation required for detector access to the middle square of intersection points (5, 6, 7, 8). Inserted into each of the twelve free space paths were compensators to eliminate the temporal separation between the signal and idler photons due to the birefringence of the Schioedtei assembly. The compensating crystals used for Schioedtei were 8x8x1 mm type II phase matched β-BBO (at angles of theta = 41.9° and phi = 30°) as Schioedtei orientation is non-collinear and there is no interaction between the pump and the compensators.

These compensators could not be used for compensation of a collinear configuration as they were phase matched for SPDC at 810 nm when exposed to a 405 nm excitation beam.

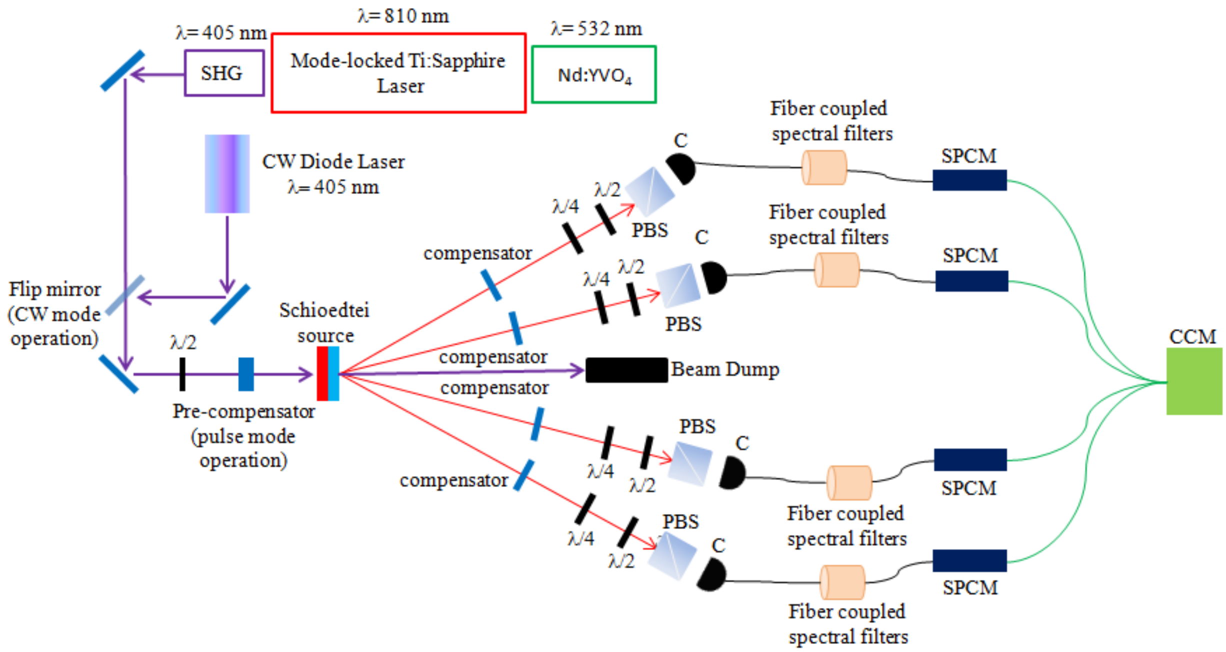


Figure 8. Experimental testbed to analyze the Schioedtei source.

Detection of the generated entangled photons was accomplished via fiber-coupled single photon counting avalanche photodiodes (APDs) (Perkin Elmer SPCM-AQ4C). Collection apertures consist of fiber-coupled collimators and spectral distinguishability of the photons is removed by fiber-coupled 2 nm bandpass filters centered at 810 nm. Coincidence detection was accomplished by connecting the four detectors to a coincidence counting module (CCM) (Branning, Trinity College) shown in Figure 9 [8].This board allowed for up to four fold coincidence detection via four input channels and eight reconfigurable outputs between any of the four input channels.

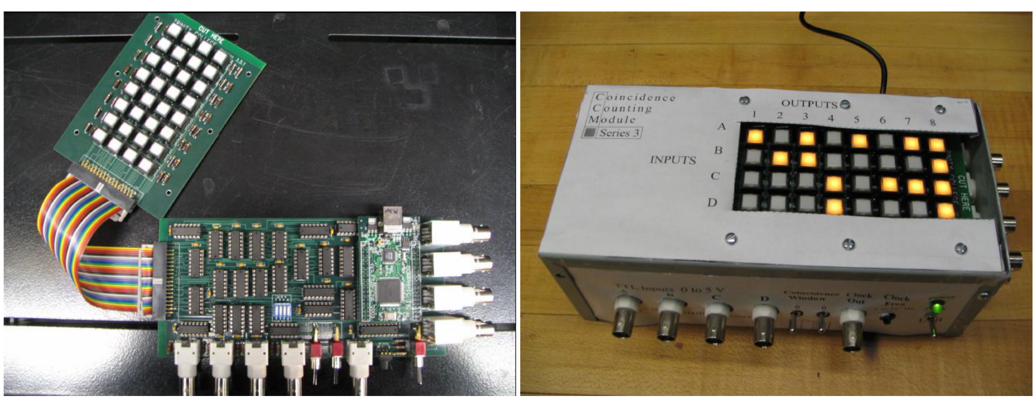


Figure 9. Coincidence counting module (Branning, Trinity College [8]) utilized in the experimental testbed in Figure 8.

A single photon cooled CCD camera (Princeton Instruments Pixis 1024BR) allowed for direct viewing of the SPDC photons produced. Utilizing this camera greatly facilitated alignment of the output of the Schioedtei assembly to the

preconfigured collection apertures of the collimators. An alignment grid with pre-determined locations for spots 5,6,7,8 was used to approximately align the Schioedtei assembly to the existing collimators.

A long exposure image from the CCD camera is shown in Figure 10. The twelve overlap regions are clearly visible and the spatial symmetry of the output should be clearly noted. The orientation of the crystal assembly gives an approximate Gaussian profile on spots 5,6,7,8 and a slightly elongated profile for spots 1,2,3,4,9,10,11,12. The central bright spot shown in the middle of the image is residual 810 nm unfiltered pump beam and fluorescence from the color glass filter used to block the CCD from the 405 nm excitation beam.

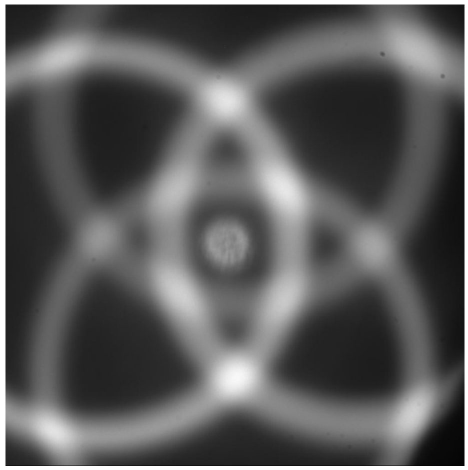


Figure 10. Experimental Data from in-house constructed crystal stack.

Once the Schioedtei crystal assembly had been set into the correct orientation via the CCD camera a 630 nm visible laser was back propagated through the collimators to align the faces to the center of the crystal, as shown in Figure 11. The collimators was reconnected and final alignment was accomplished by optimizing coincidence count rates on the selected channels on the CCM.

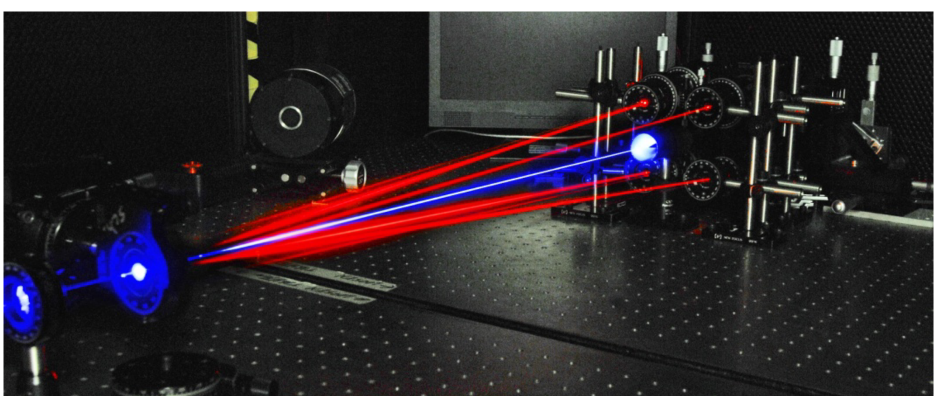


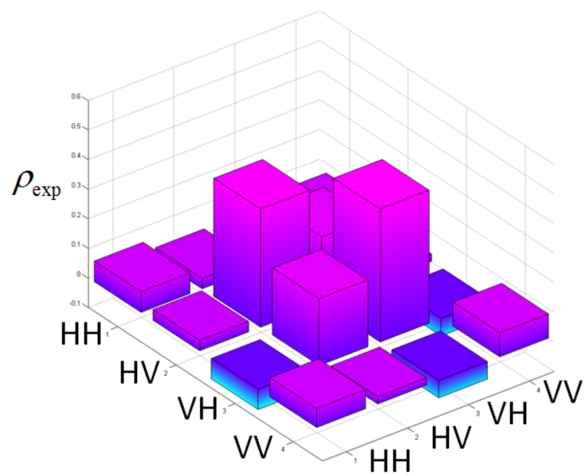
Figure 11. Alignment image of the Schioedtei crystal stack.

The experimental data shown in Figure 10 is the output of the in-house constructed Schioedtei assembly. The image shows minor levels of scattering which is attributed to the lack of optical contacting between crystal 1 and 2 in the assembly. Scattering is also due to imperfections in the crystal faces and slight angular tilting of the crystal faces with respect to one another in the custom built housing. Overall, the output SPDC rings are well defined and approximately equal in detected intensity on the CCD camera. Single channel count rates detected by the Si-APDs averaged ~20000

counts/sec. Coincidence count rates observed between any pair of spots (1,2,3,4,5,6,7,8) were ~2000 counts/sec with 4 fold coincidence count rates between 1,2,3,4 or 5,6,7,8 in the 5-10 counts/sec range. Upon alignment and optimization of each of these channels a 2-photon quantum state tomography was accomplished on any of the diametric pairs. Since reconfiguration of the collimators was required to observe spot sets 1,2,3,4 (linear arrangement) or 5,6,7,8 (square arrangement) diametric pairs were chosen within each of these sets. Insertion of quarter-wave, half-wave plates and polarizing beamsplitters in that respective order into the free-space section following the compensator and preceding the collimators was required for full tomographic analysis of the produced quantum state. The resulting density matrix can be seen in Figure 12. The resulting state, while mixed and not ideal, is a promising step towards the expected state of $\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\mathrm{HV}\right\rangle + \left|\mathrm{VH}\right\rangle\right)$ (fidelity: $F = \left\langle\psi\right|\rho_{\exp}\left|\psi\right\rangle = 0.65$, concurrence: $\mathrm{C} = 0.53$ where $\mathrm{C} = 2\left(\alpha\delta - \beta\gamma\right)$ for $\left|\psi\right\rangle = \alpha\left|HH\right\rangle + \beta\left|HV\right\rangle + \gamma\left|VH\right\rangle + \delta\left|VV\right\rangle$).

Figure 12. Experimental Tomography Data (density matrix) from in-house constructed Schioedtei crystal stack.

$$\rho_{\exp} = \begin{array}{c} \\ \mathrm{HH} \\ \mathrm{HV} \\ \mathrm{VH} \\ \mathrm{VV} \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{HH} & \mathrm{HV} & \mathrm{VH} & \mathrm{VV} \end{array} \\ \begin{bmatrix} 0.0697 & 0.0354 & -0.0688 & 0.0648 \\ 0.0354 & 0.3994 & 0.2260 & 0.0247 \\ -0.0688 & 0.2260 & 0.4496 & -0.0591 \\ 0.0648 & 0.0247 & -0.0591 & 0.0812 \end{bmatrix} \end{array}$$



To improve upon the prototype design, version II was constructed by a commercial vendor with the capability of optically contacting the crystals in the assembly. Optical contacting allowed for the removal of the dual band AR coating layers between the interfaces of crystals 1 and 2. The version II Schioedtei crystal assembly was recently delivered, though not yet fully characterized for results to be reported in this work. The initial images from the generated rings are shown in Figure 13. SPDC rings produced from the in-house designed/commercially-constructed Schioedtei assembly show greater uniformity in intensity along with a reduction in background scatter.

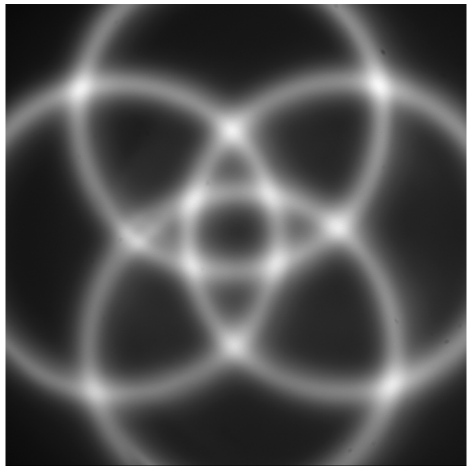
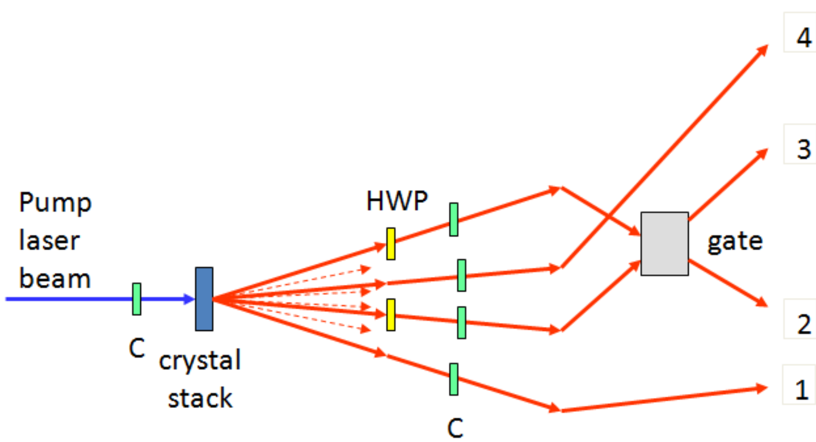


Figure 13. Experimental Data from in-house designed, commercially-constructed crystal stack.

4.2 Schioedtei source uses and implications

In this section we discuss the use of the Schioedtei source for the generation of cluster states. Cluster states play a central role in the measurement-based one-way quantum computation approach [9]. In this scheme, the entanglement resource is provided in advance through an initial, highly entangled multi-particle cluster state and is consumed during the quantum computation by means of single-particle projective measurements. The feedforward nature of the one-way computation scheme renders the quantum computation deterministic, and removes much of the massive overhead that arises from the error encoding used in the standard quantum circuit computation model [10]. Figure 14 illustrates a scheme for utilizing the output of Schioedtei to generate a four photon cluster state, $\left|C_4\right\rangle$ [11]. This particular example employs the spots 1,2,3,4 and requires insertion of two half-wave plates and a controlled-phase (CPhase) gate. This scheme could be expanded to include the other eight spots to generate even larger cluster states. Such experiments are currently being explored in-house.



$$\left|C_4\right\rangle = \frac{1}{2}\left(\left|HHHH\right\rangle_{1,2,3,4} + \left|HHVV\right\rangle_{1,2,3,4} + \left|VVHH\right\rangle_{1,2,3,4} - \left|VVVV\right\rangle_{1,2,3,4}\right)$$

Figure 14. Experimental setup for 4-qubit cluster state generation utilizing Schioedtei crystal source.

An advantage of the Schioedtei configuration is the diversity of states that it is capable of generating. Schioedtei allows for the direct generation of the (unnormalized) state $|HV\rangle \pm e^{i\varphi}|VH\rangle$ along with the generation of the state $|HH\rangle \pm e^{i\varphi}|VV\rangle$ with the addition of a half-wave plate. In addition, separable states such as $|HV\rangle \pm e^{i\varphi}|VV\rangle$ or $|HV\rangle \pm e^{i\varphi}|HH\rangle$ can also be directly generated with clever combinations of the twelve output intersections and proper compensation.

A path towards increasing the useable photon count rate in Schioedtei is the integration of the GVM phase matching constraint [5] into the crystal construction. A GVM-matched configuration is possible by alternating reduced thickness Schioedtei and α-BBO layers (α-BBO is used as a compensator; there is no second order nonlinear effect in α-BBO crystal due to the centric symmetry in its crystal structure). A source of this nature would not only provide six spatially separate entangled pairs, but also alleviate the need for spectral filtering of the photons. An increase in useable signal rates of 10X over a typical type II source is realizable with GVM matching.

5. SUMMARY

This paper has described the initial work on a new type II SPDC source design, designated Schioedtei. Schioedtei allows for the generation of six pairs of entangled photons per pass through the type II crystal assembly. This configuration surpasses the typical single entangled pair generated per pass found in standard type II SPDC sources. Useable rates of two and four fold coincidence events have been observed from Schioedtei thus showing its feasibility as a direct generation source of entangled photons for quantum optics/entanglement experiments. The six pairs of photons produced are directly applicable to the generation of larger entangled states for use in cluster state quantum computing. The utility of the Schioedtei source is (i) it produces a more compact experimental setup compared to conventional multi-stage down-conversion configurations, (ii) it generates additional states beyond those produced in standard SPDC sources, whose variety and number (iii) more easily facilitates the creation of higher-order entangled states.

6. ACKNOWLEDMENTS

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